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CARBON FOOTPRINTING

Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia

Wahidul K. Biswas

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Abstract
Purpose With building construction and demolition waste accounting for 50 % of land fill space, the diversion of reusable materials is essential for Perth”s environment. The reuse and recovery of embodied energy-intensive construction materials during civil engineering works programs can offer significant energy savings and assist in the mitigation of the carbon footprint.
Methods A streamlined life cycle assessment, with limited focus, was carried out to determine the carbon footprint and embodied energy associated with a 100-m section of road base. A life cycle inventory of inputs (energy and materials) for all processes that occurred during the development of a 100-m road section was developed. Information regarding the energy and materials used for road construction work was obtained from the Perth-based firm, Cossill and Webley, Consulting Engineers. These inputs were inserted into Simapro LCA software to calculate the associated greenhouse gas emissions and embodied energy required for the construction and maintenance of a 100-m road section using. Two approaches were employed; a traditional approach that predominantly employed virgin materials, and a recycling approach.
Results and discussion The GHG emissions and embodied energy associated with the construction of a 100-m road section using virgin materials are 180 tonnes of CO_2-e and 10.7 terajoules (TJ), respectively. The substitution of crushed rock with recycled brick road base does not appear to reduce the carbon footprint in the pre-construction stage (i.e. from mining to material construction, plus transportation of materials to the construction site). However, this replacement could potentially offer environmental benefits by reducing quarrying activities, which would not only conserve native bushland but also reduce the loss of biodiversity along with reducing the space and cost requirements associated with landfill. In terms of carbon footprint, it appears that GHG emissions are reduced significantly when using recycled asphalt, as opposed to other materials. About 22 to 30 % of greenhouse gas (GHG) emissions can be avoided by replacing 50 to 100 % of virgin asphalt with Reclaimed Asphalt Pavement (RAP) during the maintenance period.
Conclusions The use of recycled building and road construction materials such as asphalt, concrete, and limestone can potentially reduce the embodied energy and greenhouse gas emissions associated with road construction. The recycling approach that uses 100 % reused crushed rock base and recycled concrete rubble, and 15 % RAP during the maintenance period could reduce the total carbon footprint by approximately 6 %. This large carbon saving in pavement construction is made possible by increasing the percentage of RAP in the wearing course.

Keywords Carbon footprint · Civil works · Recycling · Streamlined LCA

1 Introduction

Road infrastructure projects have a significant carbon footprint. The extent to which modern production and consumption impacts the environment is increasingly becoming a topical issue with the depletion of fossil fuel energy resources, climate change pressures associated with greenhouse gas (GHG) emissions and continuing deforestation for land (Finch 1992; Zhang et al. 2000). The initial impact of construction and infrastructure management on the environment results from the energy and products consumed in infrastructure construction and

Responsible editor: Mary Ann Curran

W. K. Biswas (✉)
Sustainable Engineering Group, Curtin University,
Perth, WA 6845, Australia
e-mail: w.biswas@curtin.edu.au

production; however, the impacts continue throughout the operation, maintenance, refurbishment and demolition stages of construction.

The use of energy in producing road construction materials, such as asphalt, limestone and crushed rubble base, directly or indirectly, contribute to GHG emissions and is a major factor in the overall environmental impacts of road infrastructure projects (Suzuki and Oka 1998). In Australia, for example, the construction sector—including construction of buildings and civil works—accounts for 10–20 % of the nation's primary energy usage and energy-related GHG emissions (Ballinger et al. 1995; Lawson 1996; Treloar 1997; Treloar et al. 2004).

Recent work completed for the Main Roads Department (Access Alliance 2010; AECOM 2010) has identified that construction emissions are highly site specific, with values of 92–272 tonnes of CO_2-equivalent (CO_2-e) per lane kilometre calculated for regional road upgrade projects in Western Australia (WA). In Victoria, the Mickleham Road Duplication project measured the carbon footprint of road construction and identified ways to potentially reduce and offset carbon emissions from road works. The total carbon footprint of the Mickleham Road Duplication project was 190 tonnes CO_2-e per lane per kilometre, with 75 % of emissions associated with the materials used in the construction of the road (Maguire 2009).

Life cycle assessment (LCA) is a commonly used tool in assessing the environmental impacts (e.g. carbon footprint) associated with the construction industry. Most of these LCAs are best termed as streamlined LCAs (SLCA) as they do not take into account the full life cycle of the construction materials used (i.e. mining to disposal) (Treloar et al. 2004). However, streamlined LCAs can be used as effective decision-making tools when considering environmental performance during the design process, but the loss of inventory completeness (i.e. the exclusion of the 'use' and 'disposal' stages) results in an incomplete analysis that does not strategically highlight the key carbon components of the product/process. Maguire (2009) considered pre-construction and construction stages only in road construction, taking into account direct and indirect GHG emissions, where direct emissions are the emissions from the operation of machinery and equipment on-site and indirect emissions result from the production (quarrying, processing, manufacturing) of construction materials. This streamlined LCA has also been used to choose construction materials which reduce the associated environmental impact (Ventura and Santero 2012; Trembley 2012). For example, the engineered cementitious composite overlay system reduces the total life cycle energy by 15 and 72 %, greenhouse gas (GHG) emissions by 32 and 37 %, and costs by 40 and 58 % compared to the concrete overlay system and the hot-mix asphalt overlay system respectively, over the entire 40-year life cycle (Zhang et al. 2008).

In addition to assessing these environmental impacts, another benefit of LCA is to support a decision making process with quantitative data in reviewing alternative management scenarios to improve environmental performance (Häkkinen 1994). For example, the Mickleham Road Duplication project's LCA identified ways to potentially reduce and offset the GHG emissions associated with road construction by using recycled construction materials, including a higher use of 'reclaimed asphalt products' where possible (BMD Constructions 2008).

Apart from reducing global warming impact, LCA has been applied to develop strategies for reducing life cycle energy consumption. Carlson (2011) found that the energy used for the construction, operation and maintenance of the infrastructure only equates to a small part of the energy used for traffic and therefore, the use stage requires energy efficient measures.

Only a small portion (21 %) of construction and demolition waste is recycled in Western Australia, in comparison to other Australian states (42 % for Queensland, 58 % for Victoria, 67 % for South Australia and 71 % for NSW) (Tam 2009). The increase in the recycling of construction materials could significantly reduce the environmental emissions from the construction industries in WA. The SLCA in this paper is based on selected information provided by Cedar Woods Properties Limited (CW) and its civil engineering consultants for the Harrisdale Green project, Cossill and Webley Consulting Engineers, who assess the carbon footprint and embodied energy saving opportunities associated with recycling activities in the residential sector of WA.

1.1 Recycling strategies by Cedar Woods Properties Limited, West Perth

CW's joint venture project with the Department of Housing, Harrisdale Green Estate, is a 30-ha mixed-use residential estate comprising single residential, group and mixed-use commercial lots around several landscaped public open spaces. It is a 5–7-year project with the first stage of civil works commenced in March 2010. The project includes 7.3 km of residential road construction.

CW has conducted a trial to include recycled concrete and building rubble (RCR) instead of conventional crushed rock base (CRB) for base-course material during the first construction stages of the project. It is anticipated that the use of these recycled construction materials could significantly reduce the carbon footprint of the construction project. RCR road base materials outperformed road base made from virgin sand in terms of GHG emissions (Bowman & Associates Pty Ltd 2009). The structural analysis showed that RCR material was compliant with the modified MRWA Specification 501 (MRWA 2012) with regard to particle size distribution. Other tests conducted, such as the Atterberg Limits test and the unconfined compressive strength test were in compliance with

the modified specification, and approved by Smart Growth of America (Bowman & Associates Pty Ltd 2009). This LCA was commissioned to determine the amount of embodied energy and GHG emissions avoided by using recycled material in the construction of roads within the estate.

1.2 Goal and objectives of the current project

This study is an LCA on a section of road construction work for the Harrisdale Estate project that includes the quantification and evaluation of the GHG emissions (tonnes of CO_2-e) and embodied energy (MJ) associated with the construction of a 100-m road section. In addition, the construction 'hot spots' (carbon intensive activities) arising from this project, including the manufacturing and transportation of construction materials, the construction stage and the use/maintenance stage have been included. This LCA is classified as a streamlined LCA as it finishes at the maintenance stage, and does not take into account the GHG emissions associated with the use of the roads (i.e. movement of vehicles) and disposal of the road construction materials after their service life.

2 Methodology

An LCA was carried out following four step of ISO 14040:2006 guidelines (ISO 2006: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation (as presented in the results section).

Figure 1 briefly summarises the four steps involved in the LCA. Following Todd and Curran (1999), this LCA is best termed as streamlined LCA as it does not take into account disposal stage. In addition, this research has considered an LCA with the limited focus on two impact categories only (Finkbeiner et al. 2011), i.e. global warming or climate change and embodied energy, which is because of Australian Government's recent climate change policy (carbon pricing) and Australia's commitment for meeting GHG emission target (Department of Climate Change 2006). This SLCA also complies with the guidelines developed by the University of California, Davis for conducting the pavement LCA (Harvey et al. 2011).

2.1 Goal and scope definitions

The goal is to compare the carbon footprint and embodied energy of a three-dimensional cross section of a 100-m section of road constructed using virgin and recycled materials. Two approaches are assessed—traditional and recycled (Table 1).

1. Traditional approach: new (virgin) materials are used for all stages of road construction and maintenance.

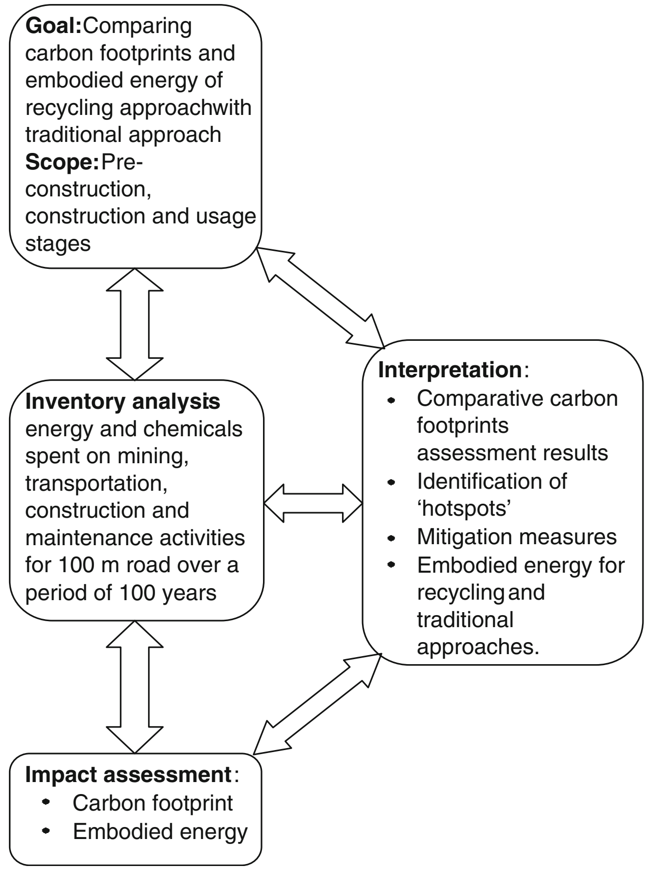


Fig. 1 Four step procedure for life cycle assessment

2. Recycling approach: this approach was developed on the basis of CW's current road construction trial in Harrisdale Green, which is in the City of Armadale where RCR from building demolition waste is to replace virgin CRB as a base-course material during the initial construction period.

Table 1 Traditional versus resource recovery road construction

	Traditional approach	Recycled approach
Initial construction[a]		
Sub-base	Virgin crushed limestone	Virgin crushed limestone
Base	Virgin CRB[c]	RCR[d]
Wearing course	Virgin asphalt	Virgin asphalt
Maintenance[b]		
Sub-base	Virgin crushed limestone	Recycled crushed limestone
Base	Virgin CRB	RCR
Wearing course	Virgin asphalt	Recycled asphalt

[a] The information is based on Cedar Wood's existing road construction project

[b] The information is based on the City of Armadale's road maintenance strategies

[c] *CRB* crushed rock base

[d] *RCR* recycled concrete rubble

The City of Armadale has adopted the following recycling strategies during the maintenance period:

a. Sub-base—generally, all the limestone material is removed, mixed and combined with fines and recompacted. 100 % reused; 15 % material added.
b. Base course—generally, the base-course material is removed, mixed and combined with fines and recompacted.100 % reused; 10 % material added.
c. Wearing course—up to 15 % of asphalt reclaimed from existing pavements (Reclaimed Asphalt Pavement or RAP) has been considered for incorporation into the lower layers of full depth (usually 250 mm) asphalt pavements. RAP material should be processed to a well-graded, free flowing and consistent state (MRWA 2011). The RAP is then combined with new materials via the hot-mix recycling process.

In this SLCA, the, carbon footprint (i.e. GHG emissions) and embodied energy directly attributable to the production and use of a 100-m section of road construction over its service life will be determined. Several different time horizons for the service life have been used in previous life cycle assessments of road construction: 40 years in Stripple (2001, as cited in Birgisdóttir 2005), 50 years in Mroueh et al. (2001, as cited in Birgisdóttir 2005) and 100 years in Olsson et al. (2006). Following the most recent study by Olsson et al. (2006), a 100-year service life was considered in this current study.

The life cycle of road works in this current study consists of three stages: pre-construction, construction and use/maintenance. The pre-construction stage includes all processes from quarrying/mining of the raw materials to the production and delivery of construction materials to the construction site. The construction stage includes machinery operations for the following sub-layers (Fig. 2):

Finally, the maintenance stage includes long-term maintenance operations to be carried out by the City of Armadale during the 100-year service life. The maintenance operation includes many activities that serve to keep the road construction in safe and acceptable condition during its service life. According to the City of Armadale, the replacement/maintenance periods for the sub-base, base course and asphalt course are typically 50 years, 25–50 years and 25 years, respectively.

As stated earlier, the car emissions associated with road usage during the service life of this road have not been considered in this study. In addition, the classification of energy in terms of primary and secondary energy sources is beyond the scope of this research. The research has been performed to provide the breakdown of embodied energy from different inputs in order to identify energy hotspots requiring further mitigation strategies.

2.2 Inventory analysis

A life cycle inventory (LCI) considers the amount of each input and output for processes which occur during the life cycle of a product/service. Undertaking an LCI is a necessary initial step in carrying out an SLCA. The inputs in terms of energy and material for road construction have been obtained from the Perth-based firm Cossill and Webley Consulting Engineers.

The LCI inputs were calculated for three life cycle stages:

2.2.1 Pre-construction stage

The information on the type of materials, thickness, length and width of a 100-m section of road were used to estimate the amount of road construction materials for sub-base, base and asphalt course layers and mountable kerb (Table 2). The road that has been considered in this study was for a residential sector and the road in the residential sector has kerbs. That was why kerb was included in this analysis. This table also shows the sources of construction materials and distance from the Harrisdale Green estate in order to calculate the distances involved in transporting the different road materials to the construction site. This distance was multiplied by the weight of the materials to produce a functional unit of tonne-kilometres (tkm). This is because the GHG emissions associated with transportation units are presented in LCA software as tkm values.

It should be noted that a portion of virgin material was added to the reused material in the recycling approach. With the exception of the recycled concrete rubble, all other

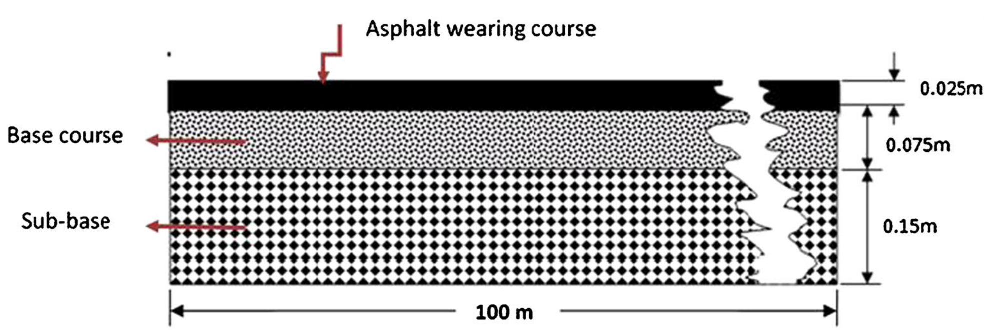


Fig. 2 Three main sub-layers of road pavement

Table 2 Specification of road base

Specimen	Source	Distance (km)	Weight (tonne/100 km of road)	tkm
Sub-base limestone	Bibra Lake,WA	12	200	3,400
Base course RCR	Maddington, WA	10	105	1,050
Wearing course—asphalt	Welshpool, WA	20	37	740
Concrete for kerb	East Perth	20	13	260
Base-course CRB	Bibra Lake,WA	12	124	1,488

construction materials used during the initial construction for the recycling approach were virgin. Therefore, the energy consumption associated with the mining of virgin asphalt and crushed limestone was considered during the initial construction stage of the recycling approach.

2.2.2 Construction stage

A questionnaire was designed to gather information from civil contractors and relevant materials suppliers (via Cossill and Webley Consulting Engineers) on energy consumption during the construction stage. Table 3 shows the energy (diesel) consumed by different machinery operations during the construction stage for sub-base, base and asphalt course sub-layers.

2.2.3 Use/maintenance stage

The maintenance periods of sub-base, base and asphalt course are 50, 25 and 25 years, respectively.

Therefore, the number of replacements of sub-base, base course and wearing-course materials over a service period of 100 years are 2, 3 and 3, respectively. Since the City of Armadale will add 10–15 % virgin materials in addition to the recycled base course and sub-base materials during maintenance projects, 10–15 % of the total carbon footprint and embodied energy associated with the production of virgin construction materials are therefore added to the total recycled approach carbon footprint. In the case of wearing course, 15 % RAP (reclaimed asphalt pavement) was added to the virgin asphalt. The wearing course made of recycled and virgin asphalt, have been found to provide the same level of service as that of new asphalt (AAPA 2011; Tao and Mallick 2009).

2.3 Impact assessment

The GHG emissions assessment of the pre-construction, construction and use of a 100-m road section involves two steps. The first step calculates the total gases produced in each process, and the second step converts these gases to CO_2-e.

2.3.1 Step 1

The input and output data in the life cycle inventory (Tables 2 and 3) was entered into the Simapro 7.3 (PRé Consultants 2011) LCA software to ascertain the GHG emissions associated with the production and use of a 100-m road section during its service life of 100 years. The recorded units of input and output data from the LCI depend on the prescribed units of the relevant materials in Simapro or its libraries (PRé Consultants 2011). The LCA library is a database, which consists of units of energy consumption, emissions factors and materials data for the production of one unit of a product. The units of input and output data from the LCI depend on the units of the relevant materials (for example kg, l, MJ, $) in Simapro or in the libraries.

Due to the absence of Australian databases in the software (i.e. libraries for RCR and CRB), new libraries or databases were created by using energy and material information from locally published reports and literature. This then allowed the SLCA results to be representative of Australian conditions.

Table 4 shows the emission factors with regard to materials and energy consumption; the inputs in the LCI were then multiplied by the respective emission factors to determine the GHG emissions from the mining stage through to material production, including the construction and maintenance stages.

Table 3 Energy consumption of construction stage

Construction operations	Fuel consumption (litres per 100 m of civil work)
Roof rolling	6.6
Sub-base	
Grader, roller, multi tyred roller, water cart, front end loader (FEL)	691.2
Base-course	
Grader, roller, multi tyred roller, water cart, FEL	691.2
Primer seal	
Spreader truck, seal truck and roller	34.5
Wearing course	
Paving machine, roller, multi trucks	1464.0
Mountable kerb	
Kerbing machine and concrete truck	288

Table 4 Emissions factors used for GHG calculations

Inputs	Emission factors	Sources
Western Australian electricity mix	868 kg CO_2-e/MWh	Australian Database (RMIT 2007)
Articulated truck	0.124 kg CO_2-e/tkm	Australian Database (RMIT 2007)
Concrete	129 kg CO_2-e/tonne	Australian Database (RMIT 2007)
Recycled concrete rubble	3.97 kg CO_2-e/tonne	Mitchell (2012) and RMCG (2010)
Crushed rock base	6.4 kg CO_2-e/tonne	Mitchell (2012) and RMCG (2010)
Crushed limestone	7.1 kg CO_2-e/tonne	Australian Database RMIT (2007) and Ray Levin 2011, pers comm
Bitumen	666 kg CO_2-e/tonne	Australian Database (RMIT 2007)
Hot-mix		
Limestone	7.9 kg CO_2-e/tonne	Whyte (2011)
Bitumen	280 kg CO_2-e/tonne	Whyte (2011)

The library of an Australian LCA database (RMIT 2007) was used to calculate the GHG emissions from the production of construction materials such as asphalt (i.e. bitumen), ready-mix concrete, limestone, and mortar mix (lime powder, sand and cement). There is an existing database for estimating carbon footprints from the quarrying of limestone but it does not include the emissions associated with crushing limestone down to aggregates. Therefore, a separate library or database for calculating emissions from the crushing was created from energy data for local quarries, for example, Italia Stone (Ray Levin, February 2011, pers. comm.). Libraries for limestone quarrying and crushing were combined to calculate the emissions associated with the quarrying and crushing of limestone for sub-base materials.

The library for the supply chain of construction materials to the construction site was developed in order to estimate the GHG emissions arising from the transportation of materials to the site. The units for the transport library were measured in tonnes-kilometre. For example, 2,397.6 tkm was required to carry 199.8 tonne of limestone from the location of Bibra Lake, which is 12 km away from the construction site (199.8 tonne × 12 km).

The library for Western Australian electricity generation was used to calculate the GHG emissions associated with the production of RCR and CRB, these being in use as base-course applications (RMIT 2007). In addition, the Australian database for diesel engine combustion was used to calculate the GHG emissions from the construction processes (e.g. kerbing, sealing, spreading, rolling and grading) and mortar operations (RMIT 2007).

Libraries for CBR and RCR were not found in the Simapro database. Separate databases or libraries were therefore made for these materials after obtaining information from Mitchell (2012), RMCG Consultants for Business, Communities and Environment (2010) and USEPA (2003). In addition, separate libraries were developed using Simapro software to calculate the GHG emissions and associated energy consumption for recycling asphalt using the 'hot-mix' technique (Whyte 2011). Following Whyte (2011), a database for GHG emissions and the associated energy consumption for the recycling of limestone filler into base course was developed.

2.3.2 Step 2

Simapro software calculated the GHG emissions (i.e. CO_2, CH_4, N_2O) once the inputs and outputs were linked to the relevant libraries. The program sorted GHG emissions from the selected libraries, and then converted each selected GHG to CO_2 equivalents. Following IPCC's second assessment report (IPCC 1996), all GHGs are converted to an equivalent amount of CO_2 (CO_2-e).

Using the same database that was used for determining the carbon footprints, the Cumulative Energy Demand Method in the Simapro software was used to calculate the embodied energy associated with the life cycle of a 100-m road section, from the acquisition of natural resources to final consumption including mining, manufacturing, transport and maintenance.

Using the Simapro software, process flowcharts were developed to illustrate the carbon footprint and embodied energy from all processes involved in the life cycle. These process flow charts, which include both upstream and downstream processes, help identify the 'hotspot', processes or inputs causing the most GHG emissions during the life cycle.

3 Results and discussions

3.1 Carbon footprint/GHG emissions of a 100-m road section

Firstly, the GHG emissions (carbon footprint) associated with the three stages of road construction and maintenance are discussed.

3.1.1 Carbon footprint of pre-construction stage

The carbon footprint from the pre-construction stage includes the emissions associated with the mining and production of limestone, asphalt, CRB and concrete and the transportation of these materials to the construction site. Figure 3 shows the carbon footprint of the mining to material production stage for the construction of a 100-m section of road.

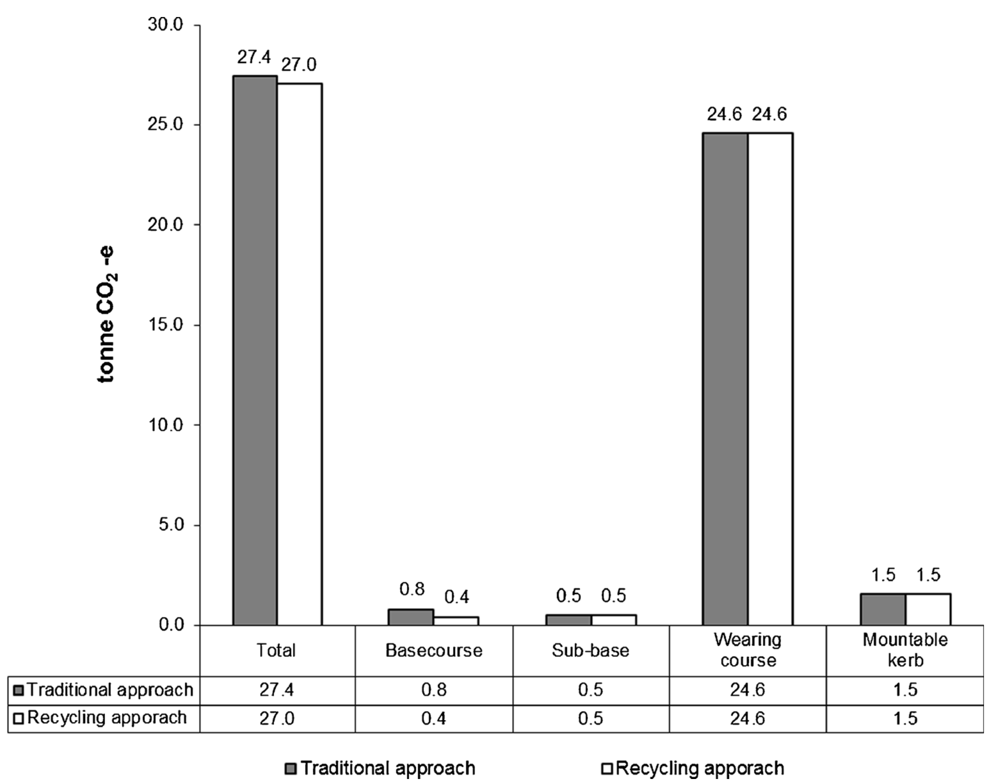
GHG emissions from CRB production are 1.75 times higher than those from RCR, and RCR is 1.2 times lighter than CRB. These factors could potentially reduce the carbon footprint associated with transportation of the material. However, only about 1.5 % of the total emissions from the pre-construction stage can be mitigated due to replacement of CRB with RCR. Therefore, the uncertainly of the mean values of the carbon footprint were determined in order to decide whether this 1.5 % difference could be ignored. The Monte Carlo Simulation (MCS) was used to analyse the uncertainty in the SLCA at the pre-construction stage, using both traditional and recycling approaches (Fig. 4). The standard deviations were only 3.3 and 3.2 % of the mean values of the carbon footprints in the pre-construction stage for the traditional and recycling approaches. These percentages were higher than the percentage differences (1.5 %) between carbon footprints when using the traditional and recycling approaches. Therefore, the contribution of RCR to GHG mitigation was ignored.

Whilst wearing course is the thinnest layer in the pavement, the GHG emissions from asphalt production were 89 % and 91 % for traditional and recycling approaches respectively. This is due to the large amount of crude oil (i.e. 10.4 TJ) that is burnt to produce 37 tonnes of asphalt for a 100 m road (explained in detail in Tables 6 and 7).

The breakdown of GHG emissions from the production of construction materials under the two different approaches is as follows: the traditional approach includes CRB (0.8 tonnes of CO_2-e, 3 %), crushed limestone (0.5 tonnes of CO_2-e, 2 %), asphalt (24.6 tonnes of CO_2-e, 89 %) and concrete for mountable kerbing (1.5 tonnes of CO_2-e, 6 %) (Fig. 2); the recycling approach includes GHG emissions from the mining to production of RCR (0.4 tonnes CO_2-e, 2 %), crushed limestone (0.5 tonnes CO_2-e, 2 %), asphalt (24.6 tonnes CO_2-e, 91 %) and mountable kerbing (1.5 tonnes CO_2-e, 6 %). These results clearly show that the replacement of CRB with RCR does not seem to afford any tangible carbon footprint reduction.

3.1.2 Carbon footprint of the construction stage

Since the same level of excavation was considered for both approaches (also confirmed by Cossill and Webley Consulting Engineers), the compactive effort of road construction (i.e. energy consumption associated with kerbing, sealing, spreading, rolling and grading processes) is similar to that for virgin and recycled materials; therefore, it is considered that the GHG emissions from the construction stage are the same for both approaches (9.2 tonnes CO_2-e).



	Total	Basecourse	Sub-base	Wearing course	Mountable kerb
Traditional approach	27.4	0.8	0.5	24.6	1.5
Recycling apporach	27.0	0.4	0.5	24.6	1.5

Fig. 3 Breakdown of the carbon footprint of the mining to material production stage for the construction of a 100-m road section

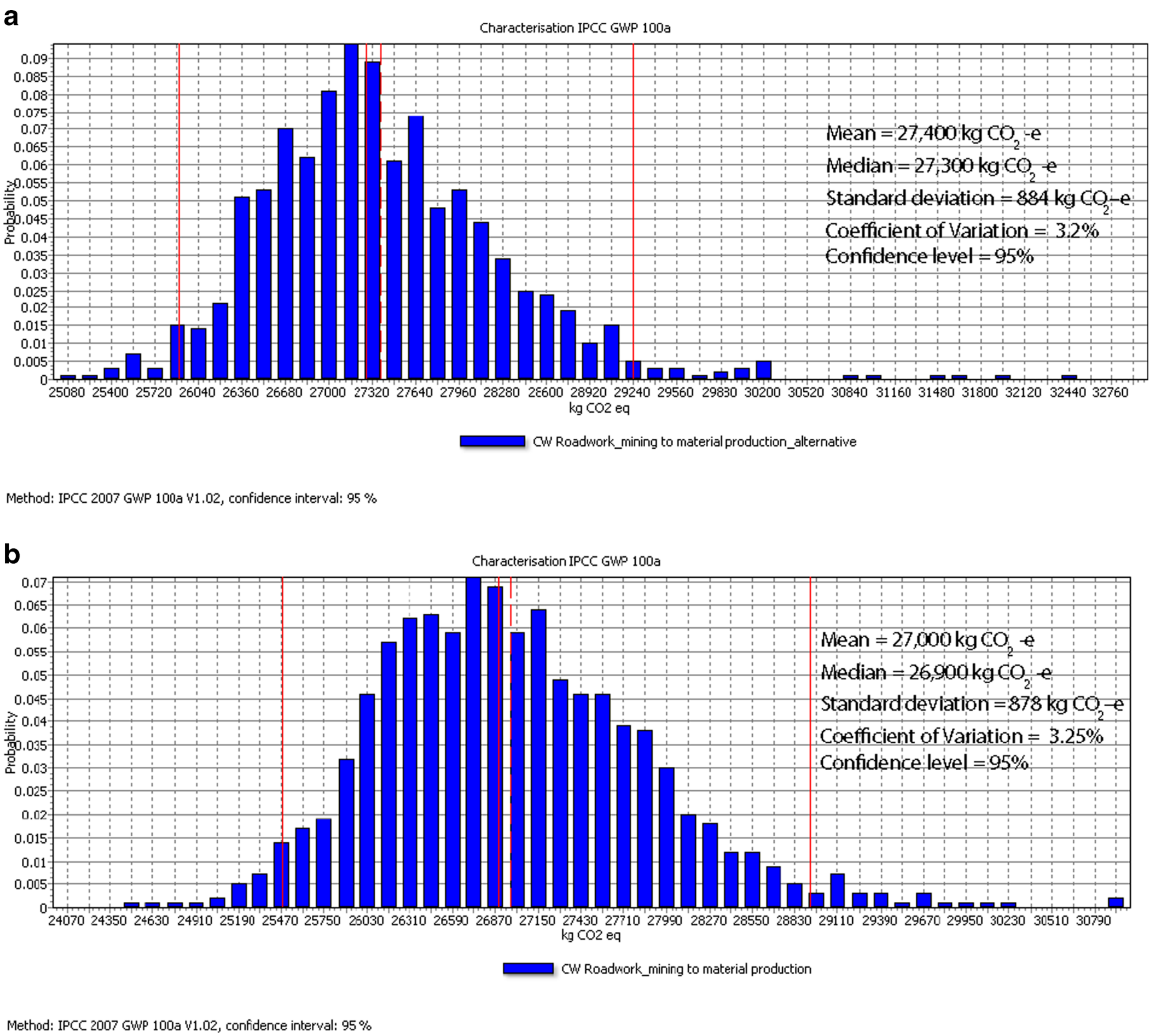


Fig. 4 Histogram from MCS calculations (1,000 runs) of the carbon footprint in the pre-construction stages using **a** traditional and **b** recycling approaches

3.1.3 Carbon footprint of the maintenance stage

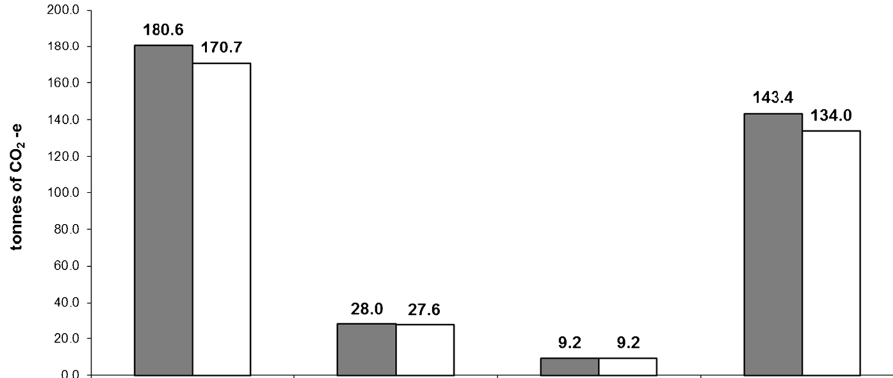
The maintenance operations over a service life of 100 years accounts for 79 % of the total life cycle GHG emissions for traditional (180.6 tonnes of CO_2-e) and recycling (170.7 tonnes of CO_2-e) approaches, respectively. This is because maintenance activities include transportation of materials, excavation, rolling, grading, paving and kerbing activities for two to three times for each construction material over the service life of the road.

Figure 5 shows the overall carbon footprint of a 100 m road. The total carbon footprint from the construction of a 100-m road section have been estimated to be 180.6 tonnes CO_2-e of GHG emissions under a traditional virgin materials approach (Fig. 2). However, if resource recovery strategies, including the use of RCR in the mining to material production stage and all recycled materials in the maintenance stage, are taken as inputs, nearly 6 % of the total carbon footprint can be mitigated.

The pre-construction (28 tonnes CO_2-e, 16 %) and construction (9.2 tonnes CO_2-e, 5 %) stages under the traditional approach produce the same amount of GHG emissions as the recycling approach, but the use stage under the traditional approach (143 tonnes CO_2-e) emits about 1.07 times more GHGs than the recycled material approach (134 tonnes CO_2-e).

GHG emissions can be further reduced by increasing the percentage of asphalt recycling during the maintenance stage.

Fig. 5 Carbon footprint of the three stages of construction for a 100-m road section using traditional and recycling approaches



	Total	Mining to material production and transportation	Construction	Use
Traditional approach	180.6	28.0	9.2	143.4
Recycling apporach	170.7	27.6	9.2	134.0

In Western Australia, a maximum of 15 % of asphalt is reclaimed for the making of the wearing course, whereas in European countries, such as Austria, Denmark, Germany, Hungary and Netherlands, the wearing courses are made of 80 to 100 % RAP (Beuving 2012). Therefore, a sensitivity analysis was carried out to observe how environmental performance varies according to recycling rates. Figure 6 shows that 22 and 30 % of GHG emissions can be avoided by replacing 15 % RAP with 50 and 100 % RAP respectively. Following the Wirtgen Group (2012), bitumen emulsions that have been formulated for treating 100 % RAP, were considered in calculating GHG emissions for this recycling rate.

3.2 Comparison with other studies

The total GHG emissions from the first two stages, including pre-construction and construction, of a 100-m road section in this study were of similar magnitude to other values reported for road construction assessment in other locations in WA. Recent work completed for the Main Roads Department (Access Alliance 2010; AECOM 2010) has identified that the average GHG emissions from pre-construction and construction stages are around 36.4 tonnes per 100-m road section calculated for regional road upgrade projects in WA, while this study found that the GHG emissions from these two stages are 37.2 tonnes CO_2-e (Fig. 5).

Similar results were also achieved by the Mickleham Road Duplication project team in Victoria, where the carbon footprint is 38 tonnes of CO_2-e per lane per 100 m, with 75 % of emissions associated with the embodied energy of materials used in construction. On-site emissions associated with construction for the Mickleham Road Duplication project were 9.5 tonnes CO_2-e per 100 m (Maguire 2009), which is approximately the same as the value obtained in the current study (9.2 tonnes CO_2-e).

3.3 Embodied energy

Embodied energy is an accounting methodology which aims to find the sum total of the energy necessary to produce a product/service during its entire lifecycle. Embodied energy is defined as the sum of energy inputs (for example fuels/power, materials, human resources) was used to make any product, from the point of extraction and refining materials, bringing it to market, and disposal or re-purposing of it (Wikipedia 2011).

Fig. 6 Sensitivity analysis of carbon footprints to asphalt recycling for a 100-m road section

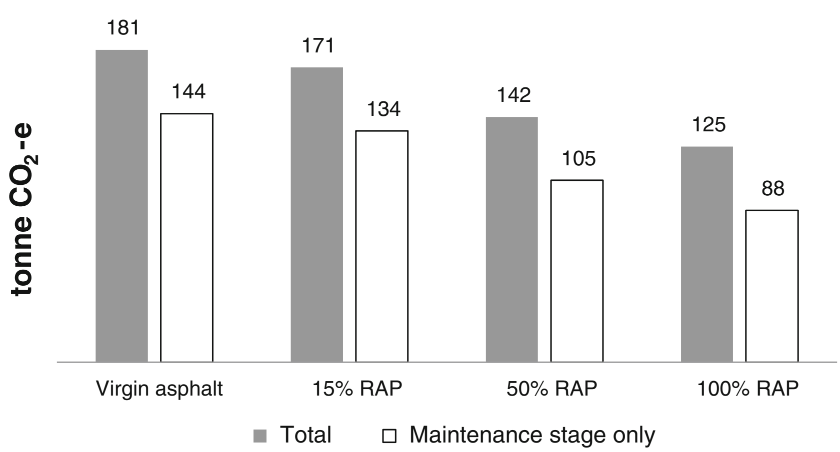


Table 5 Embodied energy (gigajoule (GJ)) of a 100-m section of road using traditional and recycling approaches

Stages	Traditional approach (GJ)	Recycling approach (GJ)	Improvement (%)
Mining to material production	2,011.0	2,000.0	1
Transportation of materials to construction site	8.7	7.5	14
Construction	137	137	0
Use/maintenance	8,505.5	8,141	4
Total	10,662.2	10,221	4

The choice of materials and construction methodology can significantly vary the amount of embodied energy in a product/service. Typically, the embodied energy of a material is often related back to the overall operating energy of the product/service as a measure of understanding the relative value of the embodied energy. Generally, the more highly processed the material, the higher the embodied energy.

The embodied energy of a 100-m section of road for traditional and recycling approaches is 10,662 and 10,221 GJ, respectively (Table 5). The mining to material production, transportation, construction and use stage consumes 2,011, 8.7, 137 and 8,506 GJ, respectively, under the traditional approach. The use of RCR reduces the energy consumption in transportation by 14 % during the initial construction stage. This reduction is predominantly because RCR is lighter than CRB and so produces less transportation emissions.

Approximately 356 GJ of net energy savings can be obtained by recycling construction materials during the use/maintenance stage, the equivalent of 51 MWh of electricity. This saved energy is equivalent to the energy needed to provide electricity to three Australian families over a period of 6 years (George Wilkenfeld and Associates 1998).

3.4 Identification of 'hotspots'

Using the Simapro LCA software, process flowcharts were developed to illustrate the GHG emissions and embodied energy from all processes involved in the life cycle of the construction of a 100-m road work section.

Tables 6 and 7 were drawn from the process flow charts, showing the relationship between the carbon footprint, embodied energy and the key inputs used over a life cycle of a 100-m road section. This relationship identifies the 'hotspots' or the inputs causing the most significant GHG emissions and embodied energy consumption during the pre-construction, construction and use/maintenance stages.

The replacement of CRB with RCR in the initial construction stage could potentially reduce both the carbon footprint and embodied energy. Quarrying and crushing rock accounts for 2.19 % of the total GHG emissions and 0.1 % of the total embodied energy, whereas the use of RCR accounts for only

Table 6 Breakdown of carbon footprint for inputs associated with the construction of a 100-m section of road

Traditional approach			Recycling approach		
Inputs	CO_2-e (t)	Percentage (%)	Inputs	CO_2-e (t)	Percentage (%)
Crude oil for asphalt production	122.36	67.75	Crude oil for virgin asphalt production	110.7	61.2
Diesel engine for construction purposes	42.08	23.30	Energy consumption during the maintenance period	43.3	25.4
Electricity for concrete production for kerbing	7.68	4.25	Diesel engine for construction purposes	9.2	5.4
Diesel oil for quarrying and crushing rocks	3.96	2.19	Recycling of asphalt (hot-mix) during service life	4.13	3.6
Articulated truck	3.03	1.68	Recycling of limestone	3.2	1.9
Diesel and electrical energy for limestone	1.49	0.83	Electricity for concrete production for kerbing	2.2	1.3
			Articulated truck	0.7	0.4
			Diesel oil for quarrying and crushing limestone	0.6	0.4
			Diesel and electrical energy for RCR	0.6	0.3
			Recycling of concrete	0.3	0.2
Total	180.6	100.00		174.9	100.0

Table 7 Breakdown of embodied energy for inputs associated with the construction of a 100-m section of road

Traditional approach			Recycling approach		
Inputs	Embodied energy (GJ)	Percentage (%)	Inputs	Embodied energy (GJ)	Percentage (%)
Crude oil for virgin asphalt production	10,401	97.55	Crude oil for virgin asphalt production	8,841	86.50
Diesel engine for construction purposes	144	1.35	Diesel engine for construction purposes	626	6.13
Electricity for concrete production for kerbing	78	0.73	Asphalt recycling (hot-mix)	542	5.31
Articulated truck	23	0.22	Limestone recycling (hot-mix)	143	1.40
Diesel oil for quarrying and crushing rocks	11	0.10	Articulated truck	22	0.22
Energy for crushed rock	5	0.04	Electricity for virgin concrete production for kerbing	21	0.20
			Diesel oil for quarrying and crushing limestone	10	0.09
			Building concrete recycling	6	0.06
			Diesel and electrical energy for recycled concrete	5	0.05
			Concrete recycling	4	0.04
Total	10,662	100.00	Total	10,221	100.00

0.3 % of the total GHG emissions and 0.05 % of the total embodied energy.

3.4.1 Carbon hotspots

In the case of the traditional approach, the use of crude oil for asphalt production was identified as a 'carbon hotspot', as it made the single largest input contribution to GHG emissions (122.4 tonnes of CO_2-e, 68 %) (Table 6). This was followed by diesel engine fuel for construction purposes (42.1 tonnes of CO_2-e, 23.3 %), electricity generation for concrete production (7.7 tonnes of CO_2-e, 4.2 %), diesel oil for quarrying and crushing for crushed rock production (3.98 tonnes of CO_2-e, >2 %), the transportation of materials to the construction site (3.03 tonnes of CO_2-e, <2 %) and diesel and electricity energy consumption for limestone crushing (1.5 tonnes of CO_2-e, <1 %) (Table 6).

The resource recovery of construction materials, using the recycling approach during the use/maintenance stage, has been found to reduce GHG emissions from the major polluting sources. The GHG emissions from the combustion of crude oil for asphalt production can be reduced by 20 tonnes with the use of recycled asphalt during the maintenance stage (Table 6), which is roughly equivalent to taking one small car off the road over a period of 5 years (City of Wanneroo 2007). Construction activities, including scarification, rolling, grading, paving and kerbing generate the second largest portion (34.7 %) of total GHG emissions. After asphalt recycling, the recycling of concrete and limestone can further reduce GHG emissions associated with electricity generation. This benefit is also confirmed by the Mickleham Road Duplication project which identified ways to potentially reduce and offset the GHG emissions from road construction through the use of recycled construction materials. This included a further use for reclaimed asphalt products (BMD Constructions 2008).

3.4.2 Energy hotspots

Crude oil consumption for asphalt production has been found to be an energy hotspot for both traditional (i.e. 10,401 GJ) and recycling (i.e. 8,841 GJ) approaches. About 1,560 GJ of energy from crude oil can be avoided with the use of recycled asphalt for wearing-course applications over a period of 100 years (Table 7). This amount of crude oil saving is equivalent to 433.3 MWh of electricity which can meet the average electricity demand of four Australian households over a 20-year period (George Wilkenfeld and Associates 1998). Therefore, it is now a general belief in most developed countries that recycling assists in extending limited road funds where old asphalt materials are reused, thus offering significant energy savings (Oke et al. 2013).

4 Conclusions

The construction and long-term maintenance of roads in a civil works program using virgin materials can be carbon and embodied energy-intensive. In road construction, the production of asphalt itself accounts for 68 % of the total GHG emissions over the full cycle of a typical road when long-term maintenance is taken into account. This footprint can be significantly reduced through resource recovery and

the recycling of road construction materials, especially during the maintenance phase.

The substitution of crushed rock with recycled brick road base does not appear to reduce the carbon footprint in the pre-construction stage (i.e. mining to material construction plus transportation for materials to the construction site). However, embodied energy consumption can be reduced by 14 % mainly due to the transportation of lightweight RCR. Apart from carbon- and energy-saving benefits, this replacement could potentially reduce quarrying, which will not only conserve native bushland but can also reduce the loss of biodiversity. Also landfill cost and space can be avoided due to the use of C&D waste as road construction material.

Both the carbon and embodied energy hotspots are centred on the crude oil used in asphalt production, with more than a 30 % reduction in both the carbon footprint and embodied energy with the reuse of 100 % recycled asphalt in road construction.

Finally, there is a need to educate agencies, the construction industry and consumers about LCA. If this decision-making tool were to be incorporated into the bidding process it could influence contractors' bidding behaviour and encourage innovation (Harvey et al. 2010).

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